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Japan

Results of AIST Micromachine R&D Project

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Micromachine R&D Technology

29 July 1994 Industrial Science and Technology R&D Office

1. Necessity of Micromachine Technology R&D

It can be said that the ultimate goal of mechanical engineering is to enable machines to function and work in the place of human beings. To meet this need through technology, it is essential that we endow machines with human intelligence and with human-like behavior so that they can express that intelligence.

When developing the latter types of machines that can perform operations as well as humans, it is necessary that the machines themselves function on a microscopic level because the basis for human activity lies in cells and the proteins inside them.

Although the microminiaturization of the machines themselves has lagged behind the development of machines with intelligence, this is an issue that must be addressed in the future development of mechanical engineering. It is clear that in the process of making machines intelligent industrial technology has made dramatic advances that have the potential to unleash a huge technological revolution.

However, because the fields of application for microminiaturized machines has been uncertain, and huge research costs are involved, private sector research in micromachines has been limited to specific areas in the past, and the scale has been too small for us to expect a technological revolution.

Therefore, the development of micromachine technology was selected for an Industrial Science and Technology R&D project with the goal of accelerating growth not only in mechanical engineering but also in industrial technology overall.

2. Details of Micromachine Project

(1) Research Framework

Period of Research: Ten years total; Phase I: Five years beginning in 1991.

Necessary Funding: ¥25 billion; Phase I: ¥10 billion

Research System: Research was consigned to the Micromachine Center (non-profit corporation) from the New Energy and Industrial Technology Development Organization (NEDO) and R&D was conducted by the private sector. The Mechanical Engineering Laboratory, Electrotechnical Laboratory, and the National Research Laboratory of Metrology also participated in R&D.

There are 27 member companies (including three foreign companies) participating in the research conducted by the Micromachine Center representing manufacturers of electrical equipment, machinery, medical devices and precision machines.

(2) Budget

(Units: Million Yen)

Year	1991	1992	1993	1994	Cumulative Total
Initial	29	856	1,503	2,232	4,620
Supplemental		425	456	1,248	2,129
Total	29	1,281	1,959	3,480	6,749

(3) Research Methods

In micromachine technology R&D we can anticipate some of the problems that must be solved such as the fact that the effects of friction increase relatively as the size of the machines gets smaller, the fact that energy transfer becomes very difficult, etc. It is likely we will also encounter unexpected problems, so we have decided that during Phase I we will fabricate and test temporary devices, and based on the progress of that research establish a basic plan for Phase II.

(Research Methods in Phase I)

Because the specific fields of application for micromachines was uncertain at the time research began, as a start we have selected the following three areas as potential fields of application and proceeded with technical development in the form of conducting research on the functional elements in each area.

1. High Capability Maintenance System for Power Plants

   This is the development of micromachines to be used for maintenance in the narrow pipes of power plants and other facilities. It consists of a microcapsule, mother machine, and both tethered and untethered inspection modules. We have ascertained the functional elements necessary for this system (micro power generators, micro energy transfer machines, etc.), and we have conduced R&D by fabricating each of these devices.

2. Micromachine Systems for Medical Therapy

   Micromachines will be used in diagnostic and therapeutic systems inside the human body. We have conducted R&D by fabricating the micromachine devices required for catheters that can be used to diagnose and treat cerebral thrombi, cerebral aneurysms, etc.

3. Development of Microfactory Technology

   The objective of this research is to fabricate tiny precision parts for watches, cameras, electronic equipment, etc., by developing and using miniature machines that are only 2-10 times larger than the parts themselves rather than using conventional large manufacturing equipment. We have conducted R&D by fabricating these devices.

3. R&D Status Update

In terms of devices, we have conducted basic research on micromotors with ODs of only a few millimeters, various types of actuators, methods for micro-bonding of materials, etc., and have utilized the results of this research to successfully fabricate machines only a few millimeters in size.

We have included an appendix of the most significant recent results so that they can be understood visually.

4. Future Issues for the Project

In research thus far we have discovered many problems that must be overcome as we proceed with future research.

The most important of these are:

(1) Clarifying and solving problems that arise when assembling the devices into micromachines,

(2) Conducting technical evaluation of the devices and re-examining device design based on the results.

We believe that it will be necessary to focus on solutions to these problems as we proceed with the project in the future.

(Details of Problems)

(1) Clarification and Solution of Problems that Arise in Assembly

Micromachines cannot function until their individual component devices are assembled, and in this respect micromachine engineering is entirely different from microelectronics engineering.

For example, even if we fabricate a micromotor, it can only be utilized for mobility, transport and other functions after it has been installed, energy is transferred to it, and it is connected to a drive system. Moreover, in assembling a micromachine, even if we have fabricated a micromotor and a microbattery, when we actually connect them we may discover there is a problem with heat generation or that we need a technique to connect the motor to a drive system.

Therefore, along with developing each individual component, it is necessary to actually assemble these components into machines, ascertain problems that arise with assembly, and work to develop solutions to those problems as well.

By so doing, we can conduct research on fabricating even better component devices by using these problems as feedback for changing the design of the device itself, its material, etc.

(2) Technical Evaluation of Devices and Re-Examination of Designs

In manufacturing practical machines, requisite values for performance for each component device will be determined by the type of task, environment where it will be performed, etc., and if the device satisfies these requisite values, then it is acceptable.

However, in the Micromachine Project we will not be fabricating micromachines themselves that will actually perform tasks, so we cannot establish the requisite performance values for manufacturing the component devices.

As a result, even if we create a micro-sized motor, confirm that the motor turns, and measure performance values such as rotary torque, we cannot evaluate what those values actually mean in terms of practicality.

Therefore, if the objective of R&D is to create devices and we are able to microminiaturize their size, from the start we must carry out theoretical evaluations by measuring the performance of the component devices we have created, comparing that performance with theoretical values, and discovering why theoretical values are not attained. We must also conduct evaluations by tracing the various phenomena that are responsible for performance values. By so doing, we can determine for the first time what kinds of operating principles and what kinds of specifications devices must have to be suitable for micromachines.

However, the problem with this approach is that few evaluative techniques themselves exist in the microrange. Therefore, we must develop these evaluative techniques as we develop the devices.

5. Future Path

The above two problems have been central issues for the Project so far, and we must at least solve these problems during Phase II (1996-2000). Therefore, must consider the solutions themselves to these problems as the main focus of Phase II.

During Phase I we will carefully investigate whether there are other major issues to be resolved, determine approaches for solving the issues we have clarified thus far, and determine their importance during Phase II of the project while seeking advice from the Industrial Technology Council, etc.

Micro Inspection Machine

1. Size and Functions

2. Novelty

The novelty in this report is the fact that we have fabricated the first micromachine system with inspection capability. We have also developed new design technology and fabricating techniques in the creation of this system. We have made the piezoelectric actuator that generates the force for movement and the eddy current sensor that detects the cracks more compact by adding refinements to previous technology.

(1) Systems Technology

In the past research was conducted on technology for the separate component devices such as sensors and actuators or on machining techniques. However, systems technology for connecting and integrating these components was nonexistent. To create this system we developed new micromachine design technology and micromachine fabrication technology such as machining and bonding techniques. Below we describe the technology for direct bonding of different materials without the use of adhesives and for shell body fabrication technology by which we created a three-dimensional, ultra-thin structure that not only protects the micromachine from the outside, but also functions for reinforcement and heat release.

(2) Direct Bonding of Different Materials

The parts of large machines are assembled with screws, adhesives and so on. However, it is impossible to form screws smaller than microparts, and deformation or heat damage cannot be tolerated when we assemble the micromachine parts. Moreover, when adhesives are used, not only does the layer of adhesive cause errors in dimensions, but other major problems arise in creating a system such as the fact that in piezoelectric elements the piezoelectric oscillator might become stuck in the layer of adhesive and be unable to function. Therefore, no effective bonding method has been available until now.

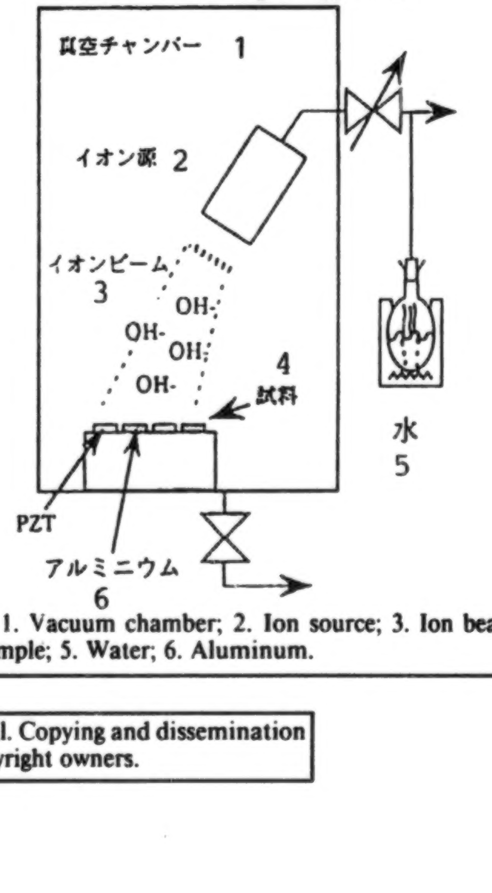
Thus, a technique for directly bonding different materials together was needed. To avoid damage to the parts we could not use excessive temperature or pressure, and we could also not use adhesives.

We solved this problem by creating a new bonding method that utilizes hydrogen bonds. In this process, water is ionized and sprayed onto the surfaces of the materials to be bonded, then the surfaces are pressed together by special holders, and bonding is achieved by hydrogen bonds that are formed by heat and pressure.

We expect that we will be able to bond many different types of materials with this new process, and thus far we have realized direct bonding of aluminum and ceramic, aluminum and silicon, etc., and obtained bonding strengths that can withstand practical use.

In this micro inspection machine we have used this technique for direct bonding of the actuator, which is a piezoelectric element, and the inertial body (aluminum: See diagram).

Schematic Drawing of Apparatus



Key: 1. Vacuum chamber; 2. Ion source; 3. Ion beam; 4. Sample; 5. Water; 6. Aluminum.

(3) Shell Body Fabrication

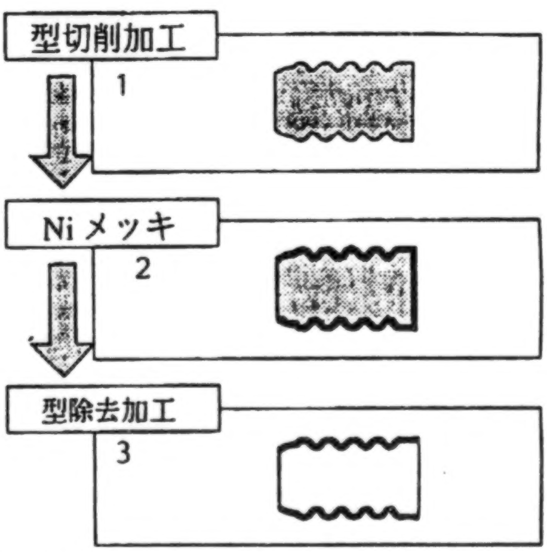
To protect the micromachine from foreign substances such as dust in the microenvironment, we need a strong, ultra-lightweight package. On standard machines we can bend thin metal plates and weld them, but with micro-order thicknesses the thin plates would be melted by welding, so conventional technology cannot be used. Integrated circuit technology has created microshapes in two dimensions, but until now we three dimensional fabrication of ultra-thin structures has not been realized.

Therefore, we developed a technique for forming a shell body (a three-dimensional structure) utilizing a unique method.

In this process, first we cut a microshape form using precision machining techniques at a high-speed machining center. Then we covered this form with a special metal plating that remains uniform with respect to small irregularities in shape. Finally we removed the form using micro electric discharge fabrication and etching techniques to create a shell body consisting of the metal plating alone.

This fabrication technique combines fabricating processes from different fields such as precision machining, metal plating, micro electric discharge and etching, and enables fabrication of a hollow, three-dimensional, ultra-thin microstructure with a complex shape, which has never been achieved before.

For this micro inspection machine we created an ultra-lightweight package that is 60 μm thick, 5.5 mm in diameter, and weighs a mere 0.084 grams.



Key: 1. Machining of form; 2. Nickel plating; 3. Removal of form.

3. Reasoning Behind This Micromachine

Mobility mechanisms for large machines such as automobiles, for example, generally use wheels. In a microenvironment, however, the effects of the friction that accompanies rotation are very great with mobility mechanisms such as wheels. Moreover, when the size of the motor becomes smaller, the force that it generates also becomes smaller, and it cannot perform work efficiently. Furthermore, in micromachines with their tiny volumes, the energy density becomes greater, and because micromachines become very hot with just a small expenditure of energy, there has been a problem with motorized drives that use electric current since in principle electric current is easily converted to heat.

In this micro inspection machine we solved that problem by employing an inching drive mechanism that uses a piezoelectric actuator. Piezoelectric phenomena are not easily converted to heat. Moreover, with this mechanism the machine can lift items several tens of times its own weight, which means it has an excellent power/weight ratio. We have achieved a lightweight structure thanks to the shell body forming technology, and this enables us to control both up/down and left/right movements, which has never been realized before.

Because we could not use screws or adhesives in assembling the micromachine parts, we bonded the parts together with the bonding technique we created to overcome this problem.

4. Future Fields of Application

We believe this micromachine system can be used for inspection of various types of piping in power plants, and in gas lines, water lines, and automobile tubing.

Important issues to be addressed in moving toward practical application in the future include communications and control techniques that enable untethered control by radio or that operate a number of micromachines together as a group.

5. Related Reports

(1) This is the first report on the Micro Inspection Machine

(2) We have made the following report on the technique for direct bonding of different materials.

Date: 31 Aug 1993 Event: 3rd IUMRS-ICAM Conference Title: Novel Bonding Technique between Dissimilar Materials by Forming Interface Hydrogen Bridges Content: Bonding aluminum and silicon in a wet process

Next report: Bonding of a piezoelectric element (PZT) and aluminum, and a PZT and copper in a dry process

(3) We have made the following report on shell body fabrication.

Date: 15 Oct 1992 Event: 3rd Micromachine and Human Science Conference Title: Fabrication of a Shell Body Microcar Content: Microcar body fabrication

Next report: Applications of shell body as ultra-lightweight package

6. Contact

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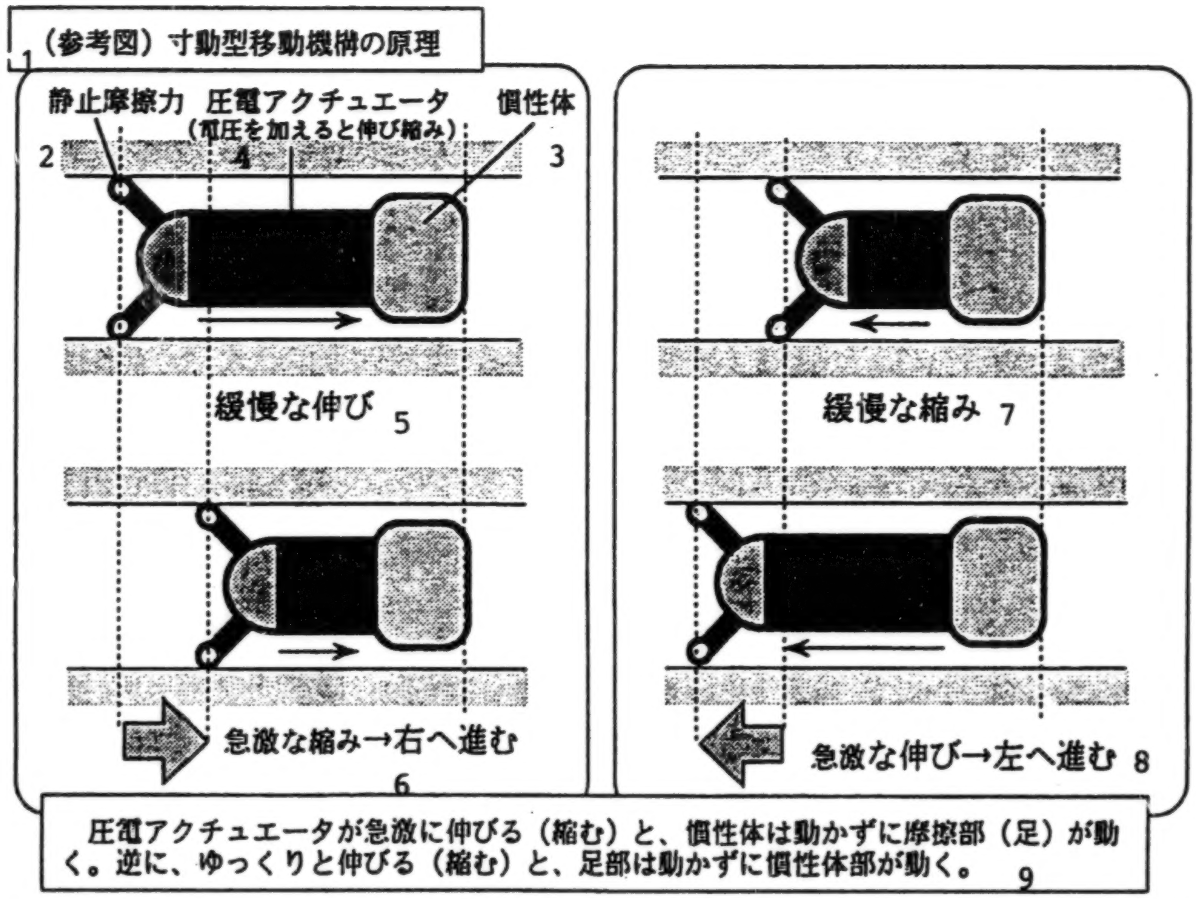


Key: 1. (Reference drawing) Principle of Inching Drive Mechanism; 2. Stationary friction force; 3. Inertial body; 4. Piezoelectric actuator (expands and contracts when voltage is applied); 5. Slow expansion; 6. Rapid contraction = movement to the right; 7. Slow contraction; 8. Rapid expansion = movement to the left; 9. When the piezoelectric actuator rapidly expands (or contracts) the frictional members (legs) move without moving the inertial body. Conversely, when it expands (or contracts) slowly, the inertial body moves without the legs moving.

Micro Photoelectric Devices

1. Advantages of Micro Photoelectric Devices for Micromachines

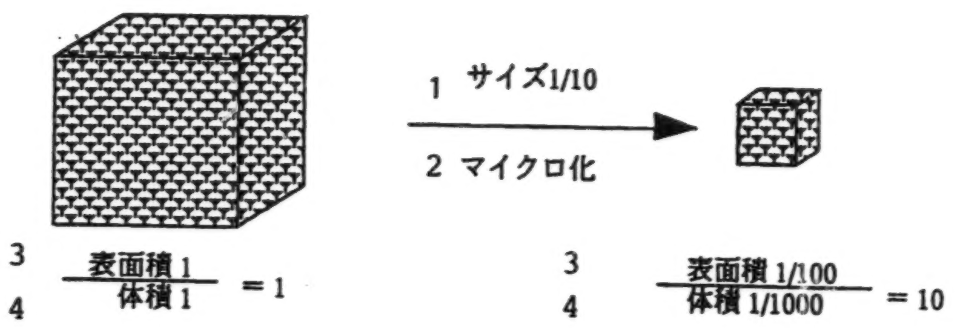
When micromachines are supplied with power via an electric line, the rigidity of the electric line (wire) interferes with the operation of the micromachine, so there is a strong need for a wireless means of supplying energy. Among the various methods of supplying wireless energy, light can be transmitted through air and water, it has little effect on the human body or instruments, and it is clean.

A photoelectric device is formed from semiconductor material such as silicon, and it converts light to electrical energy by the photoelectric effect. Normally, photoelectric devices are mounted on a surface so they can receive light, and as the size of the micromachine gets smaller and smaller, its surface area to volume ratio becomes larger, so photoelectric devices that take in energy from the surface are advantageous. As shown in the above diagram, for example, when size is reduced to one-tenth the original size, the energy supplied per unit volume becomes ten times greater.

2. Three Photoelectric Devices for This Project

(i) Ultra-Small Energy Supply Device

When medical devices such as artificial organs are implanted in the human body, the energy for their operation must be supplied in a wireless manner from the outside. To minimize the burden, the most desirable energy supply source will be as small as possible and have the least effect on the human body. Photoelectric devices are an extremely desirable means for supplying energy from the standpoint of the safety of the organism. Moreover, many types of functional components will be mounted on the medical device, and a suitable voltage



Key: 1. Size 1/10; 2. Microminiaturization; 3. Surface area; 4. Volume

must be supplied to these components. Therefore it will be necessary to provide several photoelectric devices to supply the voltages required by the many different functional components, which means that we must fabricate ultra-small photoelectric devices. Therefore, we sought more compactness through a technique in which the voltage transformer circuit is formed on the back of the photoelectric element. We also sought to develop devices that can provide energy safely within the living organism by utilizing technology to receive light energy more efficiently.

(ii) Microphotoelectric Device for Mounting on Curved Surfaces

Multiple-function micromachines that conduct inspections and transmit will find uses both in industry, such as maintenance of piping in power plants, and in consumer items. These micromachines must drive devices such as multiple electronic circuits, sensors, etc. In this instance, multiple devices will be connected in parallel to the power source, and the voltage itself will be very low, but because power will be consumed by many devices, it will be necessary to supply the micromachines with a large current. The current from photoelectric devices is proportional to the surface area of the devices, and to supply a lot of current it is desirable to mount photoelectric devices on the greatest possible surface area. Therefore, we sought a compact, high-powered energy supply by utilizing a technique in which the fabrication process is modified so that photoelectric elements can be formed on a flexible substrate. This increases the energy-supplying surface area without changing the shape of the micromachine.

(iii) High-Voltage Microphotoelectric Device

Micromachines that are self-propelled and perform tasks in industry and consumer applications must be supplied power for their high-powered electrostatic and piezoelectric actuators. These actuators require a kind of high-voltage (several hundred volts), low-current power, but batteries and conventional photoelectric devices are insufficient to drive them. Therefore, we sought to develop a device that is compact and generates high-voltage by utilizing a technique in which a very large number of miniature photoelectric devices are connected in series on a small surface area.

Ultra-Small Energy Supply Device

1. Size and Functions

An ultra-small photoelectric device measuring 1.5mm^2 with light supplied from the outside, can even drive a commercially available, large motor that is 20mm in diameter.

2. Novelty

The novelty in this report is that we have realized a compact, high-efficiency photoelectric device by utilizing techniques for mounting circuitry on the back of the device and highly efficient photoreception.

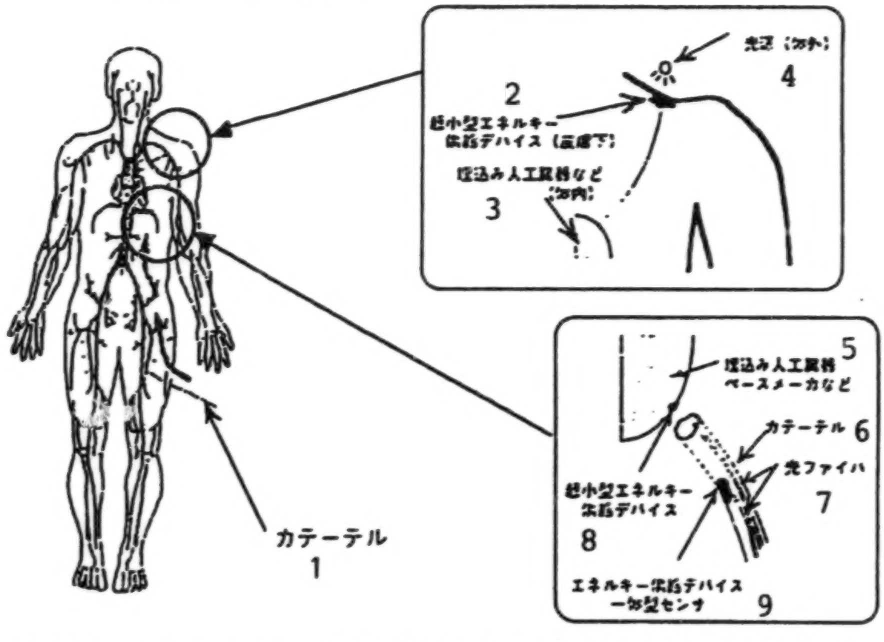
(1) Technique for Mounting Circuitry on Back

To increase the conversion efficiency of the photoelectric device, we discovered that is effective to make the back of the device (the part that does not contribute to the photoelectric effect) thin. In addition, by forming wiring that does not contribute to photoelectric conversion and circuits for converting the voltage (transformer area) in this newly created space, we made the device ultra-small. We presented our findings on the microtransformer at the "Micromachine Exhibition for Industry" (Science Museum, May 1994). This report is our first presentation of the details of the technology for the power generating mechanism.

(2) High-Efficiency Photoreception Technology

Most of the light received by a photoelectric device is reflected from the surface and lost. The ratio of this reflection differs according to the wavelength, and because light from conventional light sources such as sunlight and lamps has a variety of wavelengths, there has been no effective measure for high-efficiency photoreception. However, we achieved the highest photoreception efficiency ever of 99% by using a laser as a light source (light of a single wavelength), employing a device construction that minimizes reflection at that wavelength, and optimizing the thickness of the anti-reflection film.

Method for Utilizing Ultra-Small Energy Supply Device in Medicine



Key: 1. Catheter; 2. Ultra-small energy supply device (under the skin); 3. Implanted artificial organ (inside the body); 4. Light source (external); 5. Implanted pacemaker, artificial organ, etc.; 6. Catheter; 7. Optical fiber; 8. Ultra-small energy supply device; 9. Sensor integral with energy supply device

3. Reasoning Behind This Micromachine

In medical devices such as artificial organs that are implanted in the human body, it is desirable that the energy required for their operation be supplied in a wireless manner from the outside. Supplying energy by a photoelectric device has less effect on the human body and is considered safer than other wireless means of supplying energy (AC electric fields, radio waves). Moreover, when we consider the burden on the human body, it is desirable to make the devices as small as possible. Therefore, although it is not considered problematic with large photoelectric devices, we were able to make our device ultra-small by forming the circuitry that does not contribute to photoelectric conversion on the back of the device.

4. Future Applications

In the field of medicine, this micromachine will enable energy to be supplied safely and percutaneously (through the skin) by incorporating this ultra-small energy supply device into examination and therapeutic devices, artificial organs, pacemakers, etc., that comprise micromachines and using a catheter to provide the light.

It will be an effective means for supplying energy in environments where leakage of electric current is a problem (under water, for example) and in dangerous environments (places filled with flammable gases, for example). Thanks to the development of the microtransformer to convert the power to a voltage suitable for the component receiving the power, we can expect applications of this device in many fields in the future.

5. Contact

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Microphotoelectric Device for Mounting on Curved Surfaces

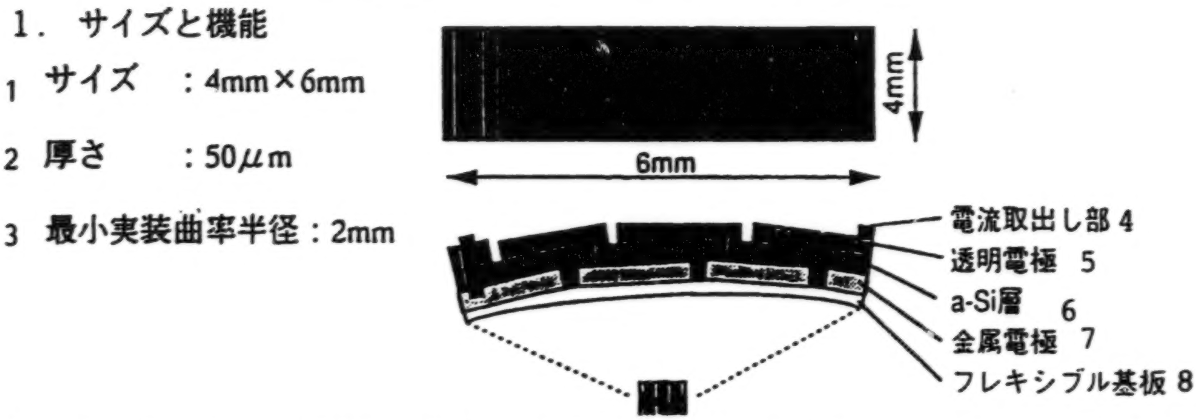
1. Size and Functions

This microphotoelectric device is a high-power photoelectric device that can be mounted on curved surfaces with a radial curvature of approximately 2mm.

2. Novelty

The novelty in this report is the fact that we have formed a photoelectric device on a flexible substrate that allows mounting on the surfaces micromachines. The problem with flexible substrates made of polymers and metal foils is that they change their properties and deform in response to heat. In conventional processes for manufacturing photoelectric devices, a special photoelectric film is formed at high temperature and then thermally

Microphotoelectric Device for Mounting on Curved Surfaces



Key: 1. Size: 4mm x 6mm; 2. Thickness: 50 μm; 3. Minimum radial curvature of mounting surface: 2mm; 4. Current extraction part; 5. Transparent electrode; 6. a-Si layer; 7. Metal electrode; 8. Flexible substrate

machined with a laser, so the photoelectric film could not be formed on a flexible substrate. To solve these problems we developed a new film-forming process and a laser machining process in which the temperature does not rise. This enables us to fabricate photoelectric devices at low temperatures.

Low Temperature Film-Forming Technique

We developed a technique for forming films of photoelectric materials at the low temperatures of 200° or less (although previously film forming was conducted at high temperatures of 1000° or more) by raising the atoms of the photoelectric material to an ionized, high-energy state (plasma state). By so doing, we were able to form films on flexible substrates that change their properties at high-temperatures. There have been previous cases of film forming techniques employing the plasma state, but this is the first one suitable for fabricating flexible photoelectric elements. Thus, we are able to form films on flexible substrates without changes in their properties or deformation.

Laser Machining Technique

In the past the cutting of grooves and making connections with the electrodes in photoelectric components have been done by laser, but there is a problem because of the high temperatures resulting from the heat of the laser. Therefore, we succeeded in suppressing heat damage to the elements by using short laser pulses.

3. Reasoning Behind This Micromachine

Because the radial curvature of a surface is large when the size of the object is large, photoelectric devices with rigid constructions have been used in the past. However, the surfaces of tiny micromachines take the shape of small curved surfaces with small radial curvatures. It will be impossible to mount rigid photoelectric devices on the small curved surfaces of micromachines without changing the shapes of the micromachines themselves. Therefore, by arranging these microphotoelectric devices as components of a photoelectric device with a flexible thin film substrate that is partitioned but connected, it will be possible to mount them easily on the surface of a micromachine and realize high power output.

4. Future Applications

As mentioned above, this microphotoelectric device that can be mounted on curved surfaces can be used for supplying energy to micromachines, and it can also be used as a power source in consumer items such as compact portable information devices like compact cameras, compact AV equipment, etc.

5. Related Reports

1) Micromachine Exhibition 11-13 May 1994
2) Article in July 1994 edition of monthly publication ASCII

6. Contact

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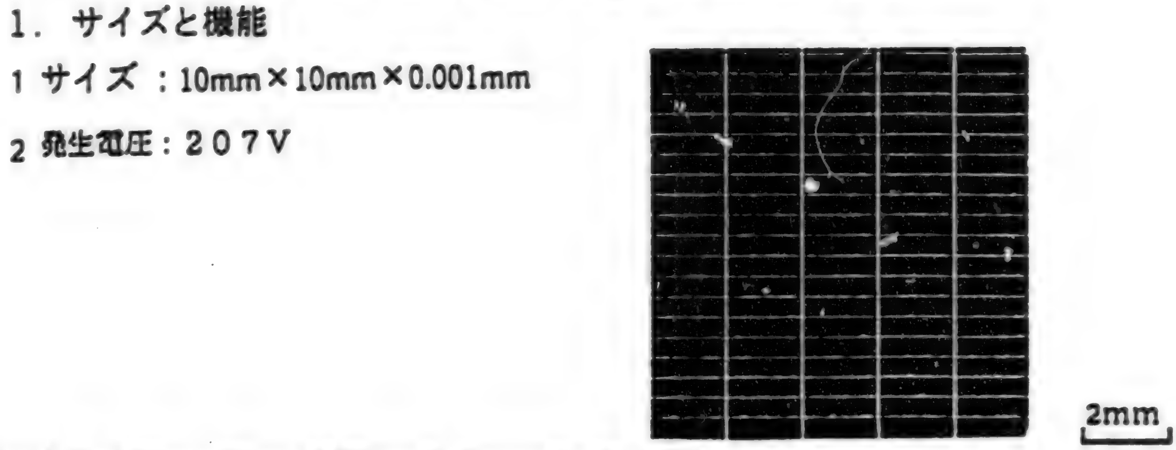
High-Voltage Microphotoelectric Device

1. Size and Functions

This is a high-voltage photoelectric device with a surface area of 10 mm^2 that can generate a high voltage of 207 V when illuminated by light. By itself this device can drive piezoelectric actuators and other elements that require high voltage.

Photo of Outside of High-Voltage Microphotoelectric Device

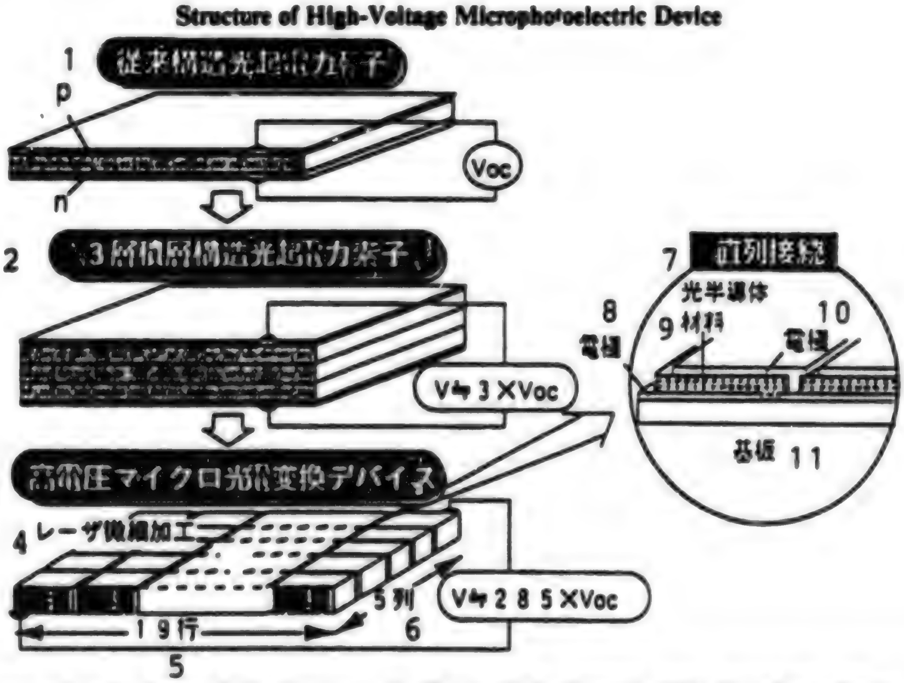


Key: 1. Size: 10mm x 10mm x 0.001mm; 2. Generated voltage: 207 V

2. Novelty

Because the voltage of a photoelectric device is determined by the material, the voltage produced by a 10 mm^2 conventional photoelectric device (solar battery) has been less than 1 V. The novelty in this report, as shown in the following diagram, is that we have successfully achieved the world's highest voltage of 207 V by connecting in series miniature photovoltaic elements (approximately 0.5 x 2.0 mm) in a three-dimensional array of 19 columns x 5 rows x 3 layers (258 steps). With this device an actuator (piezoelectric element) that requires high voltage has been directly driven using light alone for the first time in the world. This device was realized with the high-precision micromachining technique described below that employs a laser.

Structure of High-Voltage Microphotoelectric Device



Key: 1. Structure of past photovoltaic elements; 2. Photovoltaic element with three-layer laminated structure; 3. High-voltage microphotoelectric device; 4. Laser micromachining; 5. 19 columns; 6. 5 rows; 7. Connection in series; 8. Electrode; 9. Optical semiconductor material; 10. Electrode; 11. Substrate

High-Precision, Low-Damage Laser Machining Technique

To obtain a high-voltage output we took photoelectric elements with conventional structures, made three layers, and arranged them in an array of microsized photoelectric elements as a thick film. For machining we developed and used a high-aspect-shape laser micromachining technique and a three-dimensional iring machining technique.

In microsized photoelectric devices it is known that the ratio occupied by the peripheral area is large and that the properties of the peripheral area have a major effect on the properties of the device. Because with previous techniques the peripheral areas were degraded by the heat of the laser, devices for micromachines have had small photoelecric elements and large peripheral areas, and the areas affected by heat have been so large that the devices did not generate much electricity. Therefore, for micromachining we used a laser with a short wavelength, used short pulses, and optimized the machining conditions. By so doing we successfully minimized the degradation of properties in the peripheral areas.

3. Reasoning Behind This Micromachine

Research on piezoelectric and electrostatic actuators as actuators to drive micromachines has been vigorously pursued because their structures are simple and a high power output can be obtained. Because several hundred volts are needed to drive these actuators, development of a small, high-voltage energy supply device has been needed. However, batteries and conventional photoelectric devices cannot generate high voltages when they are small. By employing a high-precision micromachining technique that uses a laser we have connected a large number of microsized photoelectric elements in series in a small area, and this enabled us to develop a small, high-voltage energy supply device suitable for micromachines.

4. Future Applications

As mentioned above, this high-voltage microphotoelectric device can be used to supply energy to high-voltage drive actuators (piezoelectric and electrostatic types) for micromachines. It can also be used as a power source for consumer items compact, portable information devices like portable telephones, miniature cameras, miniature AV devices, etc.

5. Related Reports

1) Micromachine Exhibition 11-13 May 1994

2) Article in 30 June 1994 edition of NIKKEI SANGYO SHIMBUN entitled "Energy Supply by Photoelectric Methods"

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Micro Wobble Motor

1. Size and Functions

This micro wobble motor is an ultra-small motor that runs on electrostatic force, and it is capable of low-speed, high-torque rotation.

2. Novelty

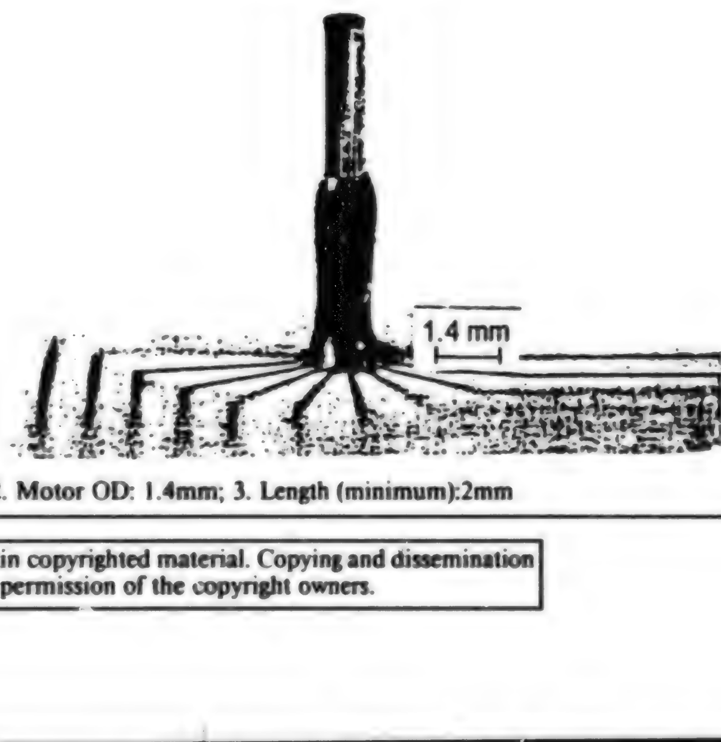
In the past there has been research on:

(1) sub-millimeter sized motors fabricated by semiconductor manufacturing technology;

(2) millimeter-sized motors fabricated by mechanical machining technology.

1．サイズと機能

1 回転軸径　：1.0mm
2 モータ外径　：1.4 mm
3 長さ（最小）：2mm



Key: 1. Diameter of rotary shaft: 1.0mm; 2. Motor OD: 1.4mm; 3. Length (minimum):2mm

However, the torque of an electrostatic wobble motor is proportional to the area of the electrodes. With thin-film motors of the former type a thick electrode cannot be formed, so the torque is very small, and it has been impossible to extract the power to the outside. With the latter type assembly of the parts is so difficult that there is a limit to reductions in size. Therefore, we developed a micromachining technique (CBP: Concentric Build-up Process) that enables fabrication of a tiny motor without assembly (assembly-less), and we successfully made a prototype micro wobble motor capable of high torque with a rotary shaft diameter of 1mm, an outside diameter of 1.4mm.

3. Reasoning Behind This Micromachine

Generally electromagnetic motors are used for large motors. The power of an electromagnetic motor is proportional to its volume, but because the power of an electrostatic motor is proportional to its area, electrostatic motors are considered advantageous for micromachines. However, handling is difficult when the parts of the motor are small, and assembling the rotor and stator within a very small space makes manufacturing extremely difficult. Therefore, we created an ultra-small motor by developing a new machining technique that does not require assembly (a technique in which the motor is assembled as it is machined).

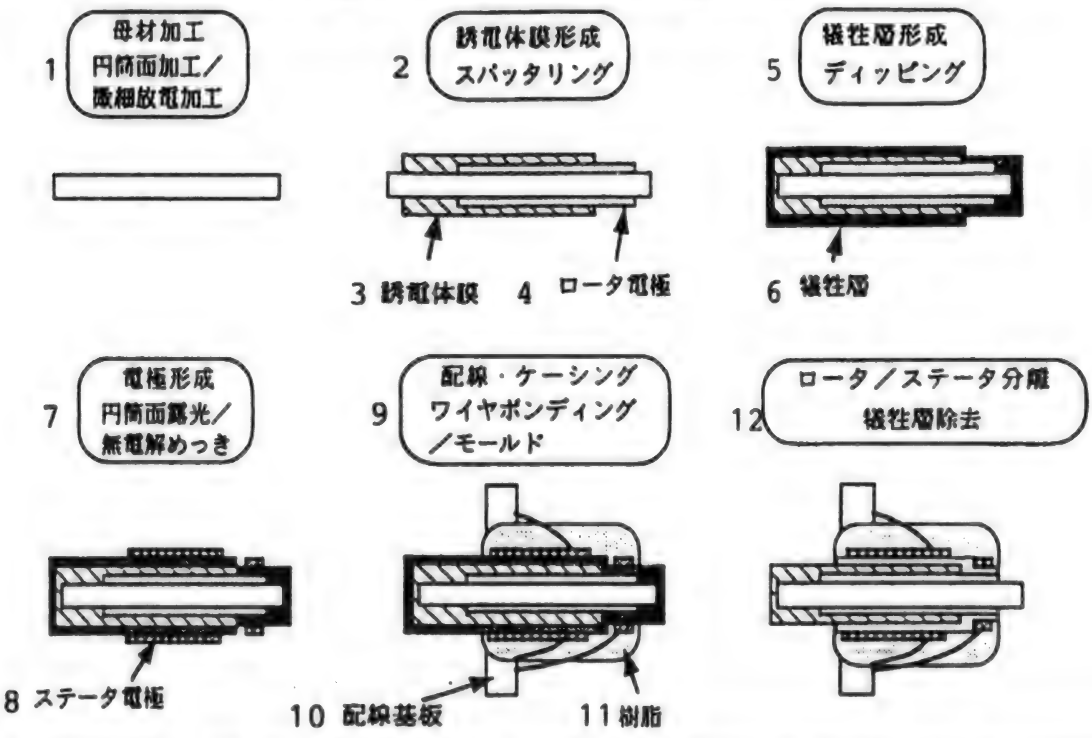
4. Manufacturing Method

As shown in the following diagram, in this machining technique various types of thin films are formed concentrically using semiconductor manufacturing techniques on a shaft fabricated by conventional machining methods. After the shape of the motor is completed, the thin film that corresponds to the gap between the rotor and the stator is removed in the final step to create a long-shafted motor without assembly.

Details of the manufacturing process are shown below. The manufacturing process can be roughly divided into six process steps. First, the cylindrical base material whose exterior has been finished to high precision by conventional machining methods is prepared. Then various types of films that make up the dielectric layer, sacrificial layer, and electrodes are formed in sequence concentrically on the cylindrical base material using film-forming and lithography techniques found in semiconductor manufacturing, and a 16-pole electrode pattern is also formed.

Then the electrodes and the wiring base are joined by wire bonding, and the stator (casing) is finished by resin

Manufacturing Process of New Micromachining Technique (CBP)



Key: 1. Machining of base material (machining of cylindrical surface/micro-electric discharge machining); 2. Formation of dielectric film (sputtering); 3. Dielectric film; 4. Rotor electrode; 5. Formation of sacrificial layer (dipping); 6. Sacrificial layer; 7. Formation of electrode (Lithography of cylindrical surface/non-electrolytic plating; 8. Stator electrode; 9. Wiring and casing (wire bonding/molding); 10. Wiring base; 11. Resin; 12. Rotor-stator separation (removal of sacrificial layer)

molding. In other words, from the rotary shaft (rotor) to the stator, the motor is formed in a single process. In the final process step the layer corresponding to the space between the rotary shaft and the stator (the sacrificial layer) is removed to complete the motor. Therefore, a micro wobble motor is formed without assembly of the rotor and stator. The motor not only realizes high torque, but the vital gap between the rotor and stator can be controlled with high precision.

Moreover, mechanical and structural materials such as metals and ceramics can be applied over the cylindrical base material, and mechanical hookup with the outside can be accomplished by machining a three-dimensional shape such as a key groove on the tip by micro-electrodischarge.

5. Future Applications

We will proceed with development toward practical application while investigating how to increase torque, extend motor life and reduce the required voltage. We plan to develop this motor as an ultra-small motor and actuator to be used in the flaw detecting device shown in the drawing that is currently under development as part of the Industrial Science and Technology R&D Project entitled "Micromachine Technology," and for use in compact electronics products with high levels of integration.

6. Related Reports

Report to media: 20 January 1994 at Tokyo branch of Matsushita Electric Industrial Company; title: Creation of "Assembly-less" Ultra-Small Motor

Conference report: 27 January 1994 at IEEE MEMS 1994; title: A Concentric Build-up Process to Fabricate Practical Wobble Motors

7. Operating Principle of Wobble Motor

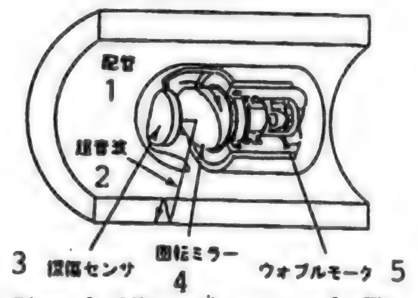
The following diagram shows the operating principle of the wobble motor. The motor consists of a rotating rotor and a peripheral stator. By applying voltage to the rotor and a specific stator electrode, an electrostatic force acts to pull the rotor toward the stator. By sequentially switching the stator electrode to which the voltage is applied, the rotor rotates by rolling along the inside of the stator.

The prototype motor we created rotates at 100 rpm when 1 kHz of drive frequency is applied, and we have confirmed a maximum rotation of 330 rpm.

8. Contact

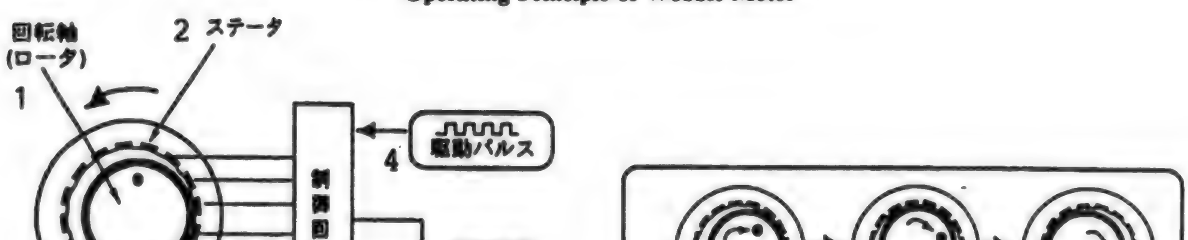
Minoru Kurokawa, Propulsion Division, Matsushita Giken TEL: 044-931-6351 FAX: 044-933-1791 (3-10 Higashimita, Tama-ku, Kawasaki-shi, Kanagawa-ken 214)

Flaw Detection Device



Key: 1. Pipe; 2. Ultrasonic waves; 3. Flaw sensor; 4. Rotating mirror; 5. Wobble motor

Operating Principle of Wobble Motor



Key: 1. Rotary shaft (rotor); 2. Stator; 3. Control circuit; 4. Drive pulse; 5. Applied voltage

Micromanipulation System (Mechanical Engineering Laboratory, AIST)

1. Function

We have developed a micromanipulation system for assembling micromachines. The system can freely manipulate microparts with dimensions of a few millimeters by employing an action similar to that of chopsticks.

There are two reasons why we chose an action similar to that of chopsticks:

(1) Micromanipulation systems that perform actions such as those of conventional robots have only three degrees of freedom along the x, y, and z axes. This system has six degrees of freedom, including rotation.

(2) Because the effects of friction increase as objects become smaller, the objects can be held sufficiently with an action similar to that of chopsticks.

2. Size

This micromanipulation system is characterized by the fact that although the size of the system itself is not small, with one unit measuring 60mm^2 x 100mm high, the movement of the glass needle tips that correspond to the chopsticks can be controlled with extremely high precision to a minimum distance (resolution) of 0.1 µm. Moreover, the range of movement of the needle tips is 130 x 130 x20 µm, which is quite large compared with their resolution.

The pair of chopsticks consists of two system units, and the sizes of the parts it can handle range from 10 µm maximum to 2 µm minimum.

Regardless of the size, no device like this system has ever been created that operates on a chopsticks principle and has six degrees of freedom.

3. Novelty

The glass needle corresponding to one chopstick is affixed to a circular needle base, and six cylindrical piezoelectric elements (material that expands and contracts in length with the flow of electric current) lie between the needle base and its circular foundation and support the needle base. The movement of the needle is controlled by varying the voltage applied to specified piezoelectric elements.

However, it is the nature of piezoelectric elements that the amount they expand when the voltage is increased is different from the amount they contract when the voltage is decreased by the same amount. Therefore, it is difficult to control the needle precisely via piezoelectric elements attached to its base.

Moreover, even if control is performed by a general purpose computer, because the piezoelectric elements respond to electricity faster than the processing speed of the computer, it has been impossible to achieve suitable control.

Therefore, we solved this problem at the laboratory by developing a new control theory in which control is achieved by estimating the content of the response before the piezoelectric element actually responds to the current.

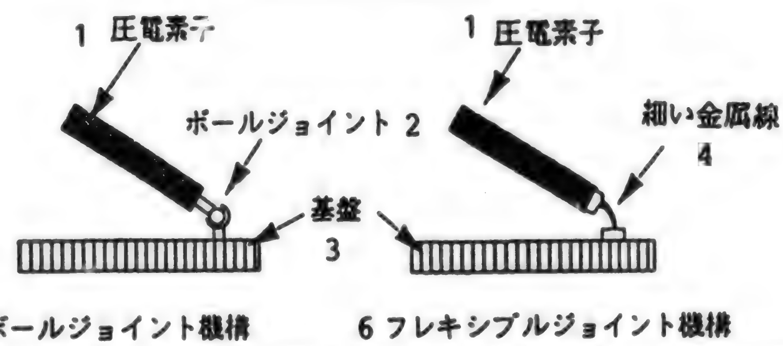
Another issue for new development has been the structure of the attachment between the piezoelectric elements and the base. The piezoelectric elements must be able to tilt freely where they are attached to the base, so something like an articulated ball joint mechanism is required.

However, a mechanism required for attaching a 2 x 3mm piezoelectric cylinder must have a diameter of 1mm or less, and it has been impossible to fabricate such an item with today's technology because it is so small. Therefore, we employed a fine metal wire for the attachment.

4. Fabrication Method

To clasp an object with chopsticks it is desirable that the tips of the chopsticks be thinner than the object. Therefore, to pick up objects with dimensions of a few microns we fabricated needle tips less than 1 µm in diameter by heating and pulling glass rods.

Attachment Mechanism



Key: 1. Piezoelectric element; 2. Ball joint; 3. Base; 4. Fine metal wire; 5. Ball joint mechanism; 6. Flexible joint mechanism

Moreover, to make the range of movement of the needle tips as great as possible while maintaining their precision of movement we settled on an arrangement with six piezoelectric elements.

5. Reasoning Behind This Micromachine

In the assembly of micromachine parts extremely high precision is required because the parts are so small. If we try to achieve this using a mechanism in which movement is performed via multiple articulated joints, such as in the arms of industrial robots, there is a problem because the error from each articulated joint is additive and the overall error becomes too great. However, with a chopsticks-like mechanism such as the one in this micromanipulator the error is not additive, and this enables extremely high-precision assembly. That is the reasoning behind this micromachine.

Moreover, friction is used to hold the parts with this chopsticks-like mechanism, so the smaller the parts are, the better the mechanism holds onto them. That is another reason for choosing this kind of micromachine.

6. Future Applications

A micromanipulation system that can freely manipulate objects with dimensions of a few microns can be used not only for micromachine assembly, but also for manipulating cells in biotechnology and for microsurgical applications in medicine.

We have plans to develop a method for detecting the microforces generated by the tips of the needles so that this manipulator can be used to hold soft objects.

7. Related Reports

We have made reports concerning theoretical issues such as design of this mechanism at conferences of the Japan Society of Mechanical Engineers, Japan Robotics Society, etc.

Moreover, the general features of the micromanipulation system mechanism (parallel link mechanism) and its theoretical basic performance have been introduced in two newspaper articles (ASAHI SHIMBUN: 18 Aug 1992, NIKKEI SANGYO SHIMBUN: 2 July 1993).

We will also present an unreleased videotape recorded in July this year of the micromanipulation system (actual item) and the combined use of two units in the manipulation of 2 μm micro-objects.

High Intensity Micro Electron Gun (Electrotechnical Laboratory, AIST)

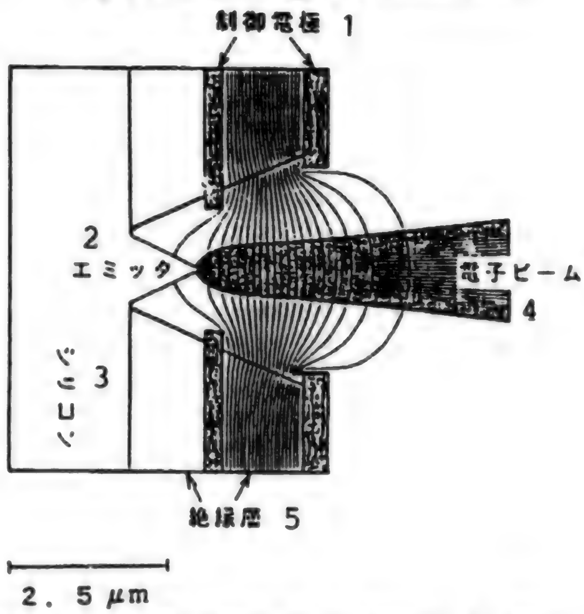
1. Size and Functions

Size (of arrayed unit): approx. 500 μm^2 x approx. 500 μm high

One form of this electron gun consists of a cone-shaped electric field discharge emitter with a sharp tip and a two-step laminated control electrode that encloses it. These are all formed into an integral unit. At our laboratory we fabricated an electron gun approximately 5 μm^2 in the form of a 10 x 10 two-dimensional array.

*Note: Generally speaking, an electron gun is a device that performs various tasks by emitting an electron beam in a vacuum. For example, in a TV picture tube the electron beam generated by the electron gun strikes a phosphorescent surface causing it to emit light and display a sharp image. Electron guns currently in use today consist of a hairpin-shaped heating filament several millimeters long and multiple electrodes several centimeters in size. These parts are machined separately and assembled by hand, so the electron guns are several centimeters or larger in size.

Fig. 1 Schematic Diagram of Electron Gun



Key: 1. Control electrodes; 2. Emitter; 3. Silicon; 4. Electron beam; 5. Insulating layer

Two problems arise when we try to microminiaturize conventional electron guns with a conventional structure and form them into an array:

(1) The whole electron gun becomes heated by the heat from the filament and breaks down,

(2) There are limits to the dimensional accuracy in machining and assembly, so the finished product will not function as an electron gun.

Therefore, in fabricating the micro electron gun we solved the heat problem by using an electric field emitter (which pulls the electrons through a vacuum by an applied voltage rather than heat) to emit the electrons in place of the filament. The emitter works based quantum-mechanics tunnelling phenomena. We solved the second

problem concerning dimensional accuracy by forming an integral unit with a laminating technique.

We successfully developed this μm-order, ultra-small, focused electron gun that has an electric field discharge emitter and a two-step laminated control electrode by employing the newest LSI manufacturing techniques and a newly developed technique for fabricating insulation thin films.

2. Novelty

The novelty in this report lies in the fact that we successfully microminiaturized each of the constituent parts of the electron gun to the μm-level using LSI manufacturing techniques and laminated them. By so doing we have realized the ultra-small electron gun that has been sought for a long time. Moreover, we have made it possible to use not only a single electron gun, but also to arrange multiple electron guns into an array in a desired area, which enables generation of an assortment of desired electron beams ranging from a very narrow beam to thick beams of various shapes. The key to this success has been the development of a new technique for forming silicon dioxide (SiO_2) thin films with sufficient insulating properties.

In this newly developed method silicon oxide (SiO) is heated by an electron beam and evaporated. At the same time, an appropriate concentration of ozone is blown across it, causing it to be deposited. This enables the formation of SiO_2 thin films with much better insulating properties than the SiO_2 thin films formed by previous methods.

3. Reasoning Behind This Micromachine

(1) The more we microminiaturize this laminated electron gun, the more we can realize a high-powered, sharp beam. In and of itself, this structural effect has significance for micromachining.

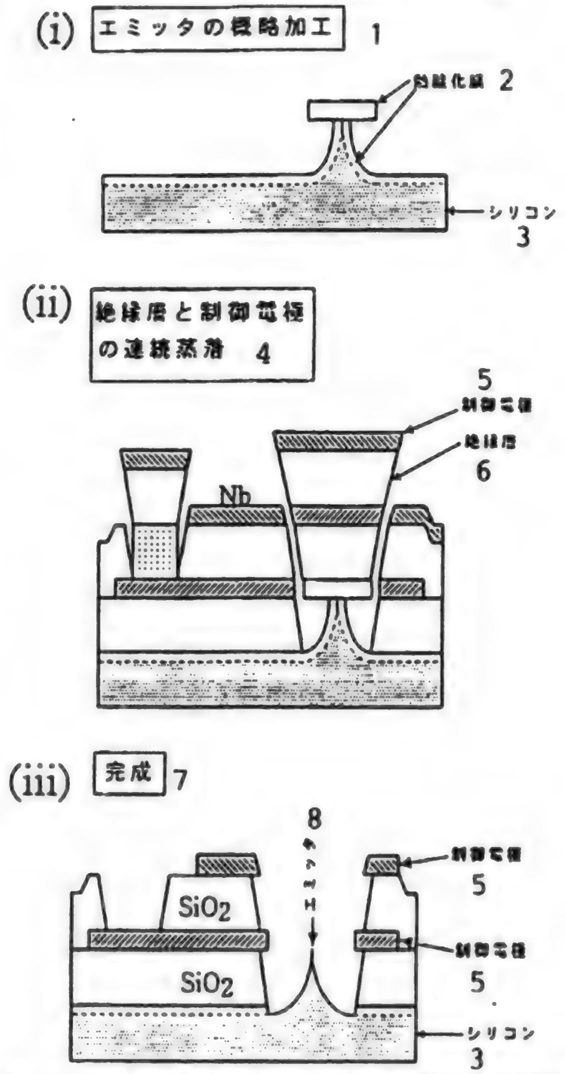
(2) This micro electron gun is fabricated not by machining and manual assembly, but by LSI manufacturing and micro-laminating techniques. These manufacturing techniques have significance for micromachining.

4 Manufacturing Method

This electron gun was created using a semiconductor micromachining technique called photofabrication. First, a silicon monocrystalline substrate is processed by dry etching, etc., to form the sharp-tipped emitter. Then the insulating layer and the two-step electrode are formed by sequential vacuum deposition. Finally the electrode aperture is removed to complete the process. What is particularly important is the technique for fabricating the SiO_2 thin film with high insulating properties that was developed in our laboratory.

To explain in slightly more detail, with the electron gun the establishment of an accurate voltage is important for

Fig. 2 Electron Gun Manufacturing Process



Key: 1. Machining of emitter outline; 2. Thermal oxide layers; 3. Silicon; 4. Sequential deposition of insulating layer and control electrodes; 5. Control electrode; 6. Insulating layer; 7. Completion; 8. Emitter

using the voltage of the control electrodes to pull the electrons from the emitter through the vacuum. If, for example, a current leak were to occur in the insulating layer, the control voltage would fluctuate, and stable operation of the electron gun would be impossible.

Generally speaking, silicon dioxide (SiO_2) is the optimal insulating material, but if a thin film is formed by the previous method of heating a piece of quartz and evaporating it, the insulating properties are severely degraded. Therefore, we selected silicon oxide (SiO) as an evaporation source in place of quartz, and devised and tested a process in which we introduced a stream of

ozone at a constant concentration as the substrate was exposed to the hot SiO vapor. The result was a film with considerably better insulting properties than those produced by previous methods that was uniform on the surface of the substrate and had properties almost equal to SiO_2 produced by bulk methods. This is the new technique we have developed.

5. Future Applications

Applications in Three-Dimensional Machining

When objects are exposed to the high-intensity electron beam generated by this electron gun and a deposition gas containing metal atoms, etc., is introduced, the gas dissociates and the metal atoms thus generated are deposited and grow. With this technique it will now be possible to fabricate μm-order microstructures with complex shapes on substrates. More specifically, it will be possible with an electron gun several centimeters in size to fabricate these kinds of structures at will in very small, enclosed spaces.

Applications in Structure Evaluation

With the electron microscopes currently in use it is impossible to observe the insides of enclosed structures and the undersides of structures. If this micro electron gun is utilized, however, these kinds of observations will be possible. This will be useful in observing the micromachine assembly process and inspecting micromachines after they have been fabricated.

6. Related Reports

The first public report of the electron gun prototype appeared on 27 August 1993 in the NIKKEI SANGYO SHIMBUN. This report concerns the newly developed insulation film forming technique and the two-dimensional (10 x 10) electron gun array realized by this process.

Micro Torsional Oscillation Element with Two Degrees of Freedom (National Research Laboratory of Metrology, AIST)

1. Outline of Technological Development

It will be necessary to measure concentrations, pressures, temperatures, etc., in the surrounding microenvironment when micromachines are used for diagnosis in factories and in microsurgery. One type of sensor for detecting information from this kind of microenvironment is an oscillation element. An oscillation element vibrates at a constant frequency under specified conditions such as we see in tuning forks and clock pendulums. However, when a force from the outside is applied and the surrounding environment (concentration, pressure, temperature, etc.) changes, the frequency changes in response to that change. Because it is possible to physically determine the relationship between a force or environmental change and the change in frequency, it is possible to use the change in frequency as a sensor to measure environmental change. For example, if an oscillation element attached to the tip of a microcatheter and made to oscillate in the bloodstream, it will be possible to measure localized changes in the body such as changes in blood sugar concentration. More specifically, one advantage of the oscillation element is that it has little effect on the body and will merely stir up the surrounding blood instead of causing an electric current to flow or bringing about chemical changes in the blood. However, miniature oscillation elements that have been proposed in the past require a large voltage to operate, and there was concern that micromachines could not supply sufficient energy transfer to drive them.

At the National Research Laboratory of Metrology we have created and developed an oscillation element that can be driven with low voltage by linking two oscillation elements together and by fabricating an oscillation element with two degrees of freedom.

2. Size

Photo 1 (not reproduced) shows a set of eight oscillation elements that were fabricated on a 4-inch silicon wafer (by the batch process). The size of a single oscillation element is $20mm^2$ x 1.2mm thick. In the future we will be able to form these oscillation elements with dimensions of several hundred microns.

(Note) Oscillation Elements Suitable for Microsensors

Among the methods for achieving oscillation there are:

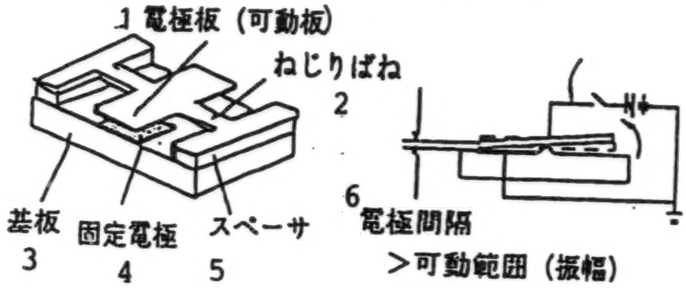
(1) The crystal method (with quartz),

(2) Oscillation of an oscillating body made of metal, etc., by causing a piezoelectric material to oscillate, and

(3) Applying an electrostatic force to an electrode made of silicon and causing it to oscillate.

The first case utilizes the following natural phenomenon: when an electric field is applied in a specific direction to a crystal, the crystal expands and contracts. It is possible to microminiaturize this but the shapes are limited. Because an oscillation-type sensor detects a specific physical quantity (such as concentration) from its mutual interaction with its surroundings as it oscillates, it is disadvantageous to have limitations on the shape of the sensor. Therefore, crystal oscillation elements are only used as temperature sensors. The second case requires assembly of the piezoelectric material and the oscillating body. There is a limit to microminiaturization because of assembly precision and so on. We believe that the third case is most suitable for micromachines because its structure is simple, there is a degree of freedom to the shape, and it can be made by batch processing through a combination of flat processes. Although we considered many types of oscillating elements, the electrostatically driven oscillating elements in previous reports had a major drawback.

Fig. 1 Example of Existing Oscillation Element



Key: 1. Electrode plate (movable plate); 2. Torsion spring; 3. Substrate; 4. Fixed electrode; 5. Spacer; 6. Gap between electrodes (greater range of motion means greater amplitude)

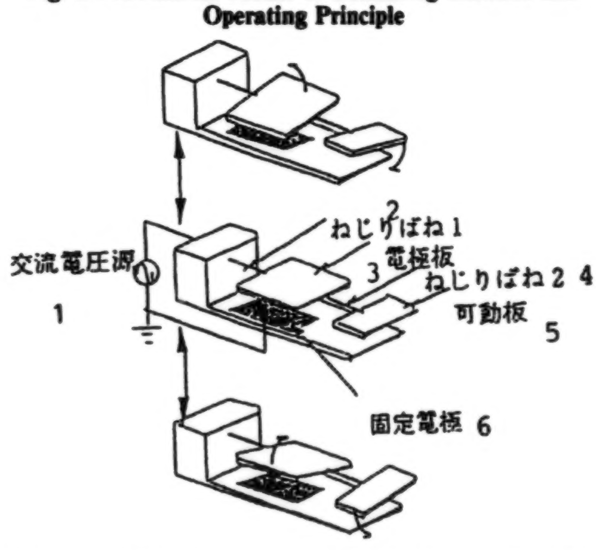
3. Novelty and Operating Principle

Figure 1 shows an example of the kind of miniature oscillating element reported in the past. When voltage is applied to the fixed electrode and to the electrode plate that is supported by a torsion spring, the electrode plate is attracted by an electrostatic attractive force and pivots on the torsion spring. By varying the voltage at a constant cycle, the electrode plate oscillates in the space between its original position and the fixed electrode. In this design the effect of the surroundings becomes stronger as the amplitude increases, which means its sensitivity as a sensor also increases. Therefore, it is desirable to have a large amplitude. To do so, however, the space between the two electrodes must be increased, but because the electrostatic attractive force is inversely proportional to the square of the distance in the gap between the electrodes, in the past it has been necessary to apply several hundred volts to overcome this increase in the gap (i.e., the increase in the amplitude) and achieve oscillation.

Figure 2 shows the operating principle of this oscillation element. The differences between this element and past oscillation elements are that the electrode plate to which the electric field is applied and the moving part form two separate oscillation elements. Because the electrode plate and the moving plate both oscillate, this is an oscillation element with two degrees of freedom. Because the moving plate moves in a direction to offset the force that causes the electrode plate to turn, the movement of the electrode plate is diminished, and this enables us to reduce the size of the gap between the electrode plate and the fixed electrode. On the other hand, the moving plate is not subject to restrictions such as the size of the gap between the electrodes and can move freely, so it can acquire sufficient amplitude. This construction allows us to use a narrow gap between the electrodes and drive the device with low voltage. Moreover, the amplitude of the oscillating element itself is large, which enables us to increase the sensitivity of the sensor.

With a drive voltage of 100V the moving plate of this oscillating element has an amplitude of about 40 μm, which confirms the usefulness of the principle behind this oscillation element. In the future we plan make improvements by optimizing design and manufacturing technique to obtain sufficient oscillation at a voltage of 5-12V, which is the operating voltage of electronic circuits.

Fig. 2 Mechanical Model of Oscillating Element and Operating Principle



Key: 1. AC voltage source; 2. Torsion spring #1; 3. Electrode plate; 4. Torsion spring #2; 5. Moving plate; 6. Fixed electrode

4. Reasoning Behind This Micromachine

(1) Structure

One of the major issues in the future of micromachine development is the difficulty of transferring energy. In other words, if we microminiaturize batteries, the power is reduced as the volume decreases, and there are problems such as heat generation with supplying power from the outside, so the supply of large amounts of power is expected to be a very difficult problem to overcome.

Therefore, it will be necessary to design the various types of sensors used in micromachines so that they operate on as little power as possible, and in that sense, the development of a micro oscillation element that runs on low voltage is very significant for micromachine development.

(2) Manufacturing

For microminiaturization we fabricated the oscillating element using the integral forming techniques of layered manufacturing to avoid assembly error. The layered assembly format itself is a micromachining process and is significant for micromachine development.

5. Manufacturing Method

The manufacturing process is shown in Figure 3, and the structure of the oscillation element in Figure 4. Essentially, this is a combination of flat processes steps on the wafer level just like the present manufacturing processes used in LSI and liquid crystal manufacturing. In other words, using the batch process for fabrication is advantageous for microminiaturization. Of course, there are many basic problems still to be solved such as techniques for bonding it to the wafer and removing residual stress.

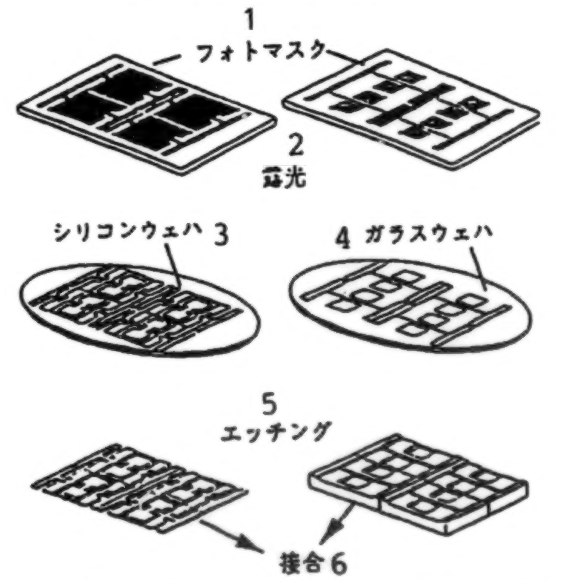
6. Future Applications

As stated in the introduction, we believe this oscillation element will be used as a sensor for micromachines such as a concentration sensor, a gyro to detect speed and direction, etc.

7. Related Reports

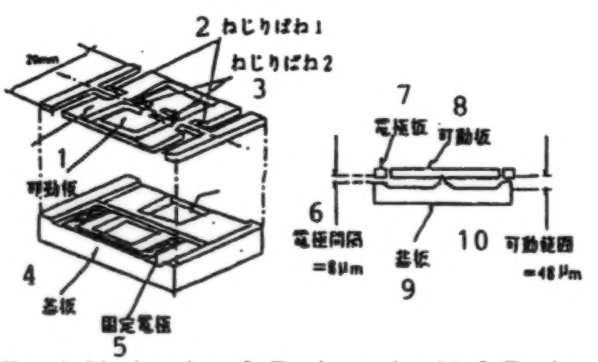
There have been no releases to the general public. We have made reports at the March 1993 Conference of the Japan Society of Precision Engineers, in June 1993 at the '93 Transducers (Yokohama, Japan), and in September 1993 at Eurosensors VII (Budapest, Hungary).

Fig. 3 Manufacturing Process



Key: 1. Photomask; 2. Exposure; 3. Silicon wafer; 4. Glass wafer; 5. Etching; 6. Attachment

Fig. 4 Structure of Oscillation Element



Key: 1. Moving plate; 2. Torsion spring #1; 3. Torsion spring #2; 4. Substrate; 5. Fixed electrode; 6. Gap between electrodes = 8 μm; 7. Electrode plate; 8. Moving plate; 9. Substrate; 10. Range of motion = 48 μm

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